

Critical review of deeply bound kaonic nuclear states

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February 9, 2008

Abstract

We critically revise the recent claims of narrow deeply bound kaonic states and show that at present there is no convincing experimental evidence for their existence. In particular, we discuss in details the claim of K^-pp deeply bound state associated to a peak seen in the Λp invariant mass spectrum from K^- nuclear absorption reactions by the FINUDA collaboration. An explicit theoretical simulation shows that the peak is simply generated from a two-nucleon absorption process, like $K^-pp \rightarrow \Lambda p$, followed by final-state interactions of the produced particles with the residual nucleus.

Over the last years the possible existence of the deeply bound states of \bar{K} in the system of nucleons was strongly discussed in the literature. Phenomenological fits to kaonic atoms fed the idea because a solution where antikaons would feel strongly attractive potentials of the order of -200 MeV at the center of the nucleus [1] was preferred. However, a deeper understanding of the antikaon optical potential demands it to be linked to the elementary $\bar{K}N$ scattering amplitude which is dominated by the presence of a resonance, the $\Lambda(1405)$, located only 27 MeV below threshold. This makes the problem a highly non-perturbative one. In recent years, the scattering of \bar{K} mesons with nucleons has been treated within the context of chiral unitary methods [2]. The explicit incorporation of medium effects, such as Pauli blocking, were shown to be important [3] and it was soon realized that the

influence of the resonance demanded the in-medium amplitudes to be evaluated self-consistently [4]. The resulting antikaon optical potentials were quite shallower than the phenomenological one, with depths between -70 and -40 MeV [5], but could reproduce equally well the kaonic atom data [6].

More recently, variational calculations of few body systems using a simplified phenomenological $\bar{K}N$ interaction predicted extremely deep kaonic states in ^3He and ^4He , reaching densities of up to ten times normal nuclear density [7, 8]. Motivated by this finding, experiment KEK-E471 used the $^4\text{He}(\text{stopped } K^-, p)$ reaction and reported [9] a structure in the proton momentum spectrum, which was denoted as the tribaryon $S^0(3115)$ with strangeness $S = -1$. If interpreted as a $(K^- pnn)$ bound state, it would have a binding energy of 194 MeV. However, in a recent work [10] strong criticisms to the theoretical claims of Refs. [7, 8] have been put forward, and a reinterpretation of the KEK proton peak has been given in terms of two nucleon absorption processes, $K^- pn \rightarrow \Sigma^- p$, $K^- pp \rightarrow \Sigma^0(\Lambda)p$, where the rest of the nucleus acts as a spectator. Similarly the peak in FINUDA proton momentum spectrum from K^- absorption on ^6Li [11] can be interpreted with the two-nucleon absorption mechanism advocated in Ref. [10], as it was accepted by the authors.

Another experiment of the FINUDA collaboration has measured the invariant mass distribution of Λp pairs [12]. The spectrum shows a narrow peak at 2340 MeV, which corresponds to the same signal seen in the proton momentum spectrum, namely K^- absorption by a two-nucleon pair leaving the daughter nucleus in its ground state. Another wider peak is also seen at around 2255 MeV, which is interpreted in Ref. [12] as being a $K^- pp$ bound state with $B_{K^- pp} = 115^{+6}_{-5}(\text{stat})^{+2}_{-3}(\text{syst})$ MeV and having a width of $\Gamma = 67^{+14}_{-11}(\text{stat})^{+2}_{-3}(\text{syst})$ MeV. In a recent work [13] we showed that this peak is generated from the interactions of the Λ and nucleon, produced after K^- absorption, with the residual nucleus. We here present some additional results, improved by the use of more realistic ΛN scattering probabilities, and summarize the present status of the field.

The reaction $(K^-)_{\text{stopped}}A \rightarrow \Lambda p A'$ proceeds by capturing a slow K^- in a high atomic orbit of the nucleus, which later cascades down till the K^- reaches a low lying orbit, from where it is finally absorbed. We assume that the absorption of the K^- takes place from the lowest level where the energy shift for atoms has been measured, or, if it is not measured, from the level where the calculated shift [6] falls within the measurable range.

In the case of ^6Li , ^7Li , ^{12}C , ^{27}Al and ^{51}V (the targets of the FINUDA experiment [12]) and ^9Be , ^{13}C , ^{16}O (to be included into the future FINUDA

experiment [14]) the absorption takes place from the $2p$ orbit, except for ^{27}Al ($3d$) and ^{51}V ($4f$).

The width for K^- absorption from pN pairs in a nucleus with mass number A is given, in local density approximation by

$$\Gamma_A \propto \int d^3\vec{r} |\Psi_{K^-}(\vec{r})|^2 \rho^2 \Gamma_m \propto \int d^3\vec{r} \frac{d^3\vec{p}_1}{(2\pi)^3} \frac{d^3\vec{p}_2}{(2\pi)^3} |\Psi_{K^-}(\vec{r})|^2 \Gamma_m(\vec{p}_1, \vec{p}_2, \vec{p}_K, \vec{r}), \quad (1)$$

where $|\Psi_{K^-}(\vec{r})|^2$ is the probability of finding the K^- in the nucleus, $|\vec{p}_1|, |\vec{p}_2| < k_F(r)$ with $k_F(r) = (3\pi^2\rho(r)/2)^{1/3}$ being the local Fermi momentum and $\Gamma_m(\vec{p}_1, \vec{p}_2, \vec{p}_K, \vec{r})$ is the in-medium decay width for the $K^-pN \rightarrow \Lambda N$ process. The structure of the integrals determining Γ_m ,

$$\Gamma_m \propto \int d^3\vec{p}_\Lambda d^3\vec{p}_N \dots K(\vec{p}_\Lambda, \vec{r}) K(\vec{p}_N, \vec{r}), \quad (2)$$

allows us to follow the propagation of the produced nucleon and Λ through the nucleus after K^- absorption via the kernel $K(\vec{p}, \vec{r})$. The former two equations describe the process in which a kaon at rest is absorbed by two nucleons (pp or pn) within the local Fermi sea, emitting a nucleon and a Λ . The primary nucleon (Λ) is allowed to re-scatter with nucleons in the nucleus according to a probability per unit length given by $\sigma_{N(\Lambda)}\rho(r)$, where $\sigma_{N(\Lambda)}$ is the experimental $NN(\Lambda N)$ cross section at the corresponding energy. We take σ_Λ cross section fitted to the data from [15, 16]:

$$\sigma_\Lambda = (39.66 - 100.45x + 92.44x^2 - 21.40x^3)/p_{LAB} \text{ [mb]}, \quad (3)$$

where $x = \text{Min}(2.1 \text{ GeV}, p_{LAB})$. In [13] a simpler parameterization for the Λ , of the type $\sigma_\Lambda = 2\sigma_N/3$ was employed, but as we shall see, this modification affects non-negligibly only the results for heavy nuclei [17].

We note that particles move under the influence of a mean field potential, of Thomas-Fermi type. The hole nucleon spectrum has an additional constant binding Δ of a few MeV that forces the maximum ΛN invariant mass allowed by our model, $m_{K^-} + 2M_p - 2\Delta$, to coincide with the actual invariant mass reached in K^- absorption leading to the ground state of the daughter nucleus, $m_{K^-} + M(A, Z) - M(A-2, Z-2)$. After several possible collisions, one or more nucleons and a Λ emerge from the nucleus and the invariant mass of all possible Λp pairs, as well as their relative angle, are evaluated for each Monte Carlo event. See Ref. [13] for more details.

Absorption of a K^- from a nucleus leaving the final daughter nucleus in its ground state gives rise to a narrow peak in the Λp invariant mass distribution, as observed in the spectrum of [12]. We note that our local

density formalism, in which the hole levels in the Fermi sea form a continuum of states, cannot handle properly transitions to discrete states of the daughter nucleus, in particular to the ground state.¹ For this reason, we will remove in our calculations those events in which the p and Λ produced after K^- absorption leave the nucleus without having suffered a secondary collision. However, due to the small overlap between the two-hole initial state after K^- absorption and the residual $(A - 2)$ ground state of the daughter nucleus, as well as to the limited survival probability for both the p and the Λ crossing the nucleus without any collision, this strength represents only a moderate fraction, estimated to be smaller than 15% in ${}^7\text{Li}$ [13].²

Our invariant mass spectra requiring at least one secondary collision of the $p(n)$ or Λ after the $K^-pp(np)$ absorption process are shown in Fig. 1 for different nuclei³, where we have applied the same cuts as in the experiment, namely $P_\Lambda > 300$ MeV/c (to eliminate events from $K^-p \rightarrow \Lambda\pi$) and $\cos \Theta_{\vec{p}_\Lambda \vec{p}_p} < -0.8$ (to filter Λp pairs going back-to-back). The maximum number of allowed secondary collisions is 2 for ${}^6\text{Li}$, 3 for ${}^7\text{Li}$, ${}^9\text{Be}$, ${}^{12}\text{C}$, ${}^{13}\text{C}$, ${}^{16}\text{O}$, 4 for ${}^{27}\text{Al}$ and 5 for ${}^{51}\text{V}$. The calculated angular distribution shown in Ref. [13] demonstrates that, even after collisions, a sizable fraction of the events appear at the back-to-back kinematics. These events generate the main bump at 2260-2270 MeV in all the Λp invariant mass spectra shown in Fig. 1, at about the same position as the main peak shown in the inset of Fig. 3 of [12]. Since one measures the Λp invariant mass, the main contribution comes from $K^-pp \rightarrow \Lambda p$ absorption (dot-dashed lines), although the contribution from the $K^-pn \rightarrow \Lambda n$ reaction followed by $np \rightarrow pn$ (dotted line) is non-negligible. It is interesting that the width of the distribution gets broader with the size of the nucleus, while the peak remains in the same location, consistently to what one expects for the behavior of a quasi-elastic peak. Let us point out in this context that the possible interpretation of the FINUDA peak as a bound state of the K^- with the nucleus, not as a K^-pp bound state, would unavoidably lead to peaks at different energies for different nuclei [18]. We finally observe that the spectra of heavy nuclei develop a secondary peak at lower invariant masses due to the larger amount of re-scattering processes. It is more pronounced than that shown in our earlier work [13], due to the use

¹ However including an additional constant binding Δ for the hole nucleon spectrum we make sure that the position of the narrow peak for ground state to ground state transition is correct.

² It should also be mentioned here that the possibility of removing two protons from the initial nucleus leading to a final $(A - 2)$ excited nucleus in the continuum without further interaction of the p or Λ is negligible due to the small overlap between these two states.

³The model presented here is based on Fermi sea approximation for original and daughter nuclei, and hence it is not valid for very small systems, like $K^- {}^4\text{He}$.

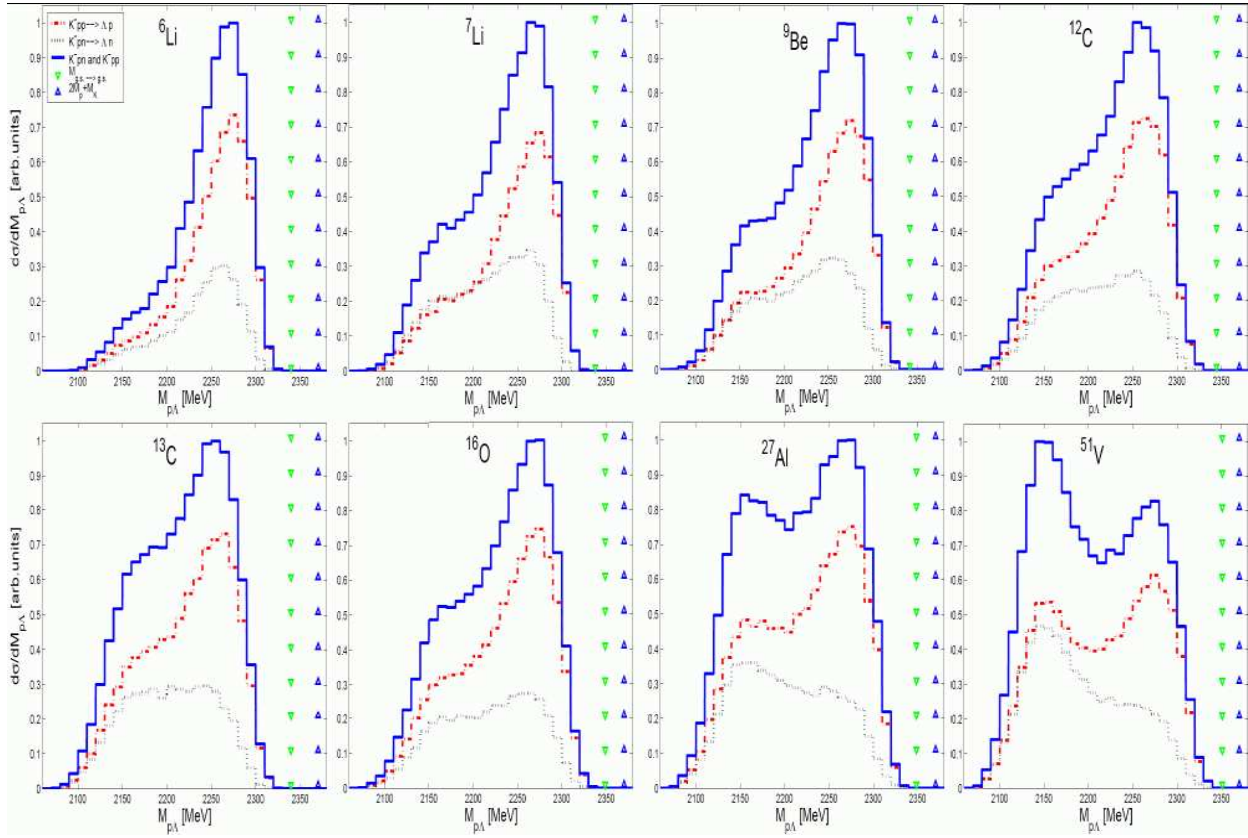


Figure 1: Λp invariant mass distribution for K^- absorption in several nuclei imposing $P_\Lambda > 300$ MeV/c and $\cos \Theta_{\vec{p}_\Lambda \vec{p}_p} < -0.8$.

here of a realistic ΛN scattering cross section. However, we want to stress that in the low invariant mass region other processes, not taken into account in our calculations, like for example one nucleon absorption, are important and may significantly modify the spectrum.

Finally, we compare our results with those presented in the inset of Fig. 3 in Ref. [12], using the three lighter targets in the same proportion as in the experiment - see Fig. 2. We note that the averaged histogram is dominated by the ^{12}C component of the mixture, due mostly to the larger overlap with the kaon wave function. As we see, our calculations are in excellent agreement with the measured spectrum in this range.

Thus, the experimental Λp invariant mass spectrum of the FINUDA collaboration [12] is naturally explained in our Monte Carlo simulation as a consequence of final state interactions of the particles produced in nuclear K^- absorption as they leave the nucleus, without the need of resorting to exotic mechanisms like the formation of a K^-pp bound state. Together with the interpretation of the proton momentum spectrum given in Refs. [10, 11], it seems then clear that there is at present no experimental evidence for the existence of deeply bound kaonic states.

Recently new results came from few body calculations, either solving Fad-

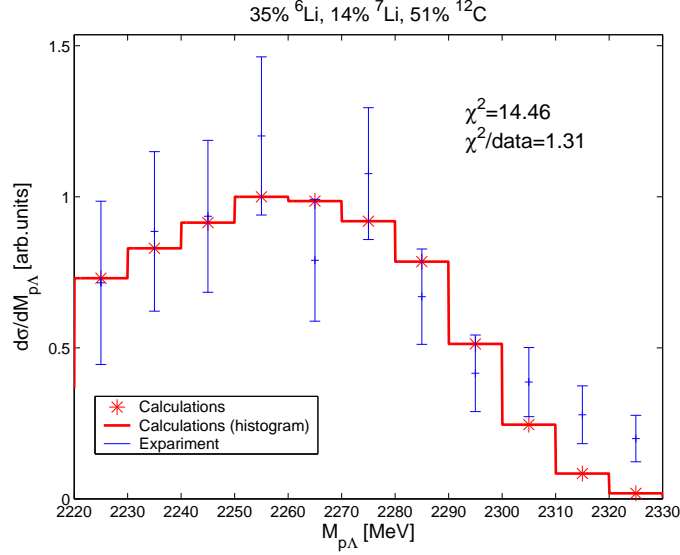


Figure 2: Invariant mass of Λp distribution for K^- absorption in light nuclei in the following proportion: 51% ^{12}C , 35% ^6Li and 14% ^7Li . Stars and histogram show our results, while experimental points and errorbars are taken from Ref. [12].

deev equations [19] or applying variational techniques [20], using realistic $\bar{K}N$ interactions and short-range nuclear correlations. These works predict few-nucleon kaonic states bound by 50-70 MeV but having large widths of the order of 100 MeV, thereby disclaiming the findings of Refs. [7, 8].

Acknowledgments. This work is partly supported by contracts BFM2003-00856 and FIS2005-03142 from MEC (Spain) and FEDER, the Generalitat de Catalunya contract 2005SGR-00343, and the E.U. EURIDICE network contract HPRN-CT-2002-00311. This research is part of the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RII3-CT-2004-506078.

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